Rockfalls Dynamics Analysis and Mass Movement Characterization based on Multi-Temporal UAV and LiDaR surveys in "Apothikes" area, Santorini Island, Greece

I. Konstantinidis[1], E. Karantanellis[1], V. Marinos[1]

(1) Laboratory of Engineering Geology & Hydrogeology, School of Geology, Aristotle University of Thessaloniki, 54124, Thessaloniki, Greece, ioakekonst@geo.auth.gr

During the last decade, there has been an increasing demand in geo-engineering society for automatically monitored areas susceptible to landslide and catastrophic rockfall events. Traditional methods were supplemented, mostly by in-situ observational methods held by experts or by point-based approaches such as inclinometers and GPS measurements. Lately, we were given the opportunity to apply active sensors such as Terrestrial Laser Scanning (TLS) technology or passive ones such as Unmanned Aerial Vehicle (UAV) photogrammetry, as a result of the introduction of innovative remote sensing technologies as a common practice. This change has led to more accurate, precise and time-effective local scale modelling of the landslide event. Specifically, Structure from Motion (SfM) methodology enabled the production of ultra high-resolution orthomosaic and Digital Terrain Models (DTMs) of hazardous regions, via detailed point clouds. The current research demonstrates a powerful approach to precisely foresee potential rockfall hazards in the area of interest, based on a multi-temporal change detection procedure in time intervals in order to prevent any undesired consequence via the integration of innovative remote sensing tools and the suitable analysis of their results.

The investigated site is located in Santorini Island, Greece and is called "Apothikes". Specifically, the area is situated in the southern part of the island, east of the Akrotiri village, on a road that leads to the only beach that lays inside the caldera region. Various rockfall incidents of significant magnitude have been recorded in the slope over the years, mainly connected with external triggering factors and especially occurring after heavy rainfall. These rockfalls have caused numerous destructions on the road and have concluded to its temporary disruption in the past. These blocks are not only confined along the road but can also reach the seacoast. The significance of this specific region in which the research is held originates from the notable human activity (hotel, residences) that takes place at the top of the slope as well as the restlessness tourist activity during the year which is especially observed in the area of the beach located directly under the prone area. Specifically, "Apothikes" comprise one of the most tourist destinations in the whole island. Consequently, it is indispensable to provide accurate and precise precognitions of any potential rockfall hazard because of their significant environmental and commercial impacts.

In general, the volcanic complex of Santorini belonged to the volcanic arc of South Aegean and is the most active globally. The commission of this complex is based lengthwise in two main volcano-tectonic lines with a NE-WS strike. The area is geologically characterized by successive alternations of volcanic beds of strong ignimbrite and soft layers of pyroclastic materials with different engineering properties. The morphology consists of very steep slopes (≤80°) with highly steep dip discontinuities (76°-90°) which have significant persistence. All these parameters constitute to differential erosion and undercut in the base of the slope which develop tensile tenses and eventually lead to the loss of the rockmass cohesion and finally the failure of the previously suspended unstable blocks of ignimbrite ($\leq 4m^3$) from a notable height (≅15m). The main failure mode comprises rock pillar detachment followed by toppling or planar sliding failure, which result to their fragmentation. The fallen blocks reveal fresh surfaces and as a result, the laterally blocks exhibit a lack of confining stress. Consequently, new cracks begin to emerge and the same process accelerates.

Analytically, in this particular case, multi-sensor fusion and multitemporal change detection techniques were performed among three different datasets derived from i) a Terrestrial Laser Scanner (TLS) during summer 2014 and ii) a UAV platform during summer of 2018 and spring of 2019 respectively. The aim of this procedure is to monitor and characterize topographical changes between different epochs for robust modelling of the rockfall's dynamics. The proposed approach of multi-sensor change detection was accomplished with the correlation of the 3 multi-epoch models in order to quantify the rockfall's displacements with computer-based methods. With the results of this comparison it was possible to classify the whole investigated area into sub-regions based on rockfall susceptibility.

In order to precisely predict potential rockfall hazards in the area we proceed to a trajectometry simulation in the prone sub-regions. The produced Digital Surface Model (DSM), from the latest acquired dataset, was converted to hillshade via QGIS3.0. The prone blocks, that we have already spot, was analyzed and their potential trajectories was specified in both 3D and 2D display. This analysis gave us the capability to estimate the outcome (energy, velocity, height and travel time) of any potential rockfall event pre and post the implementation of remedial measures. It gives us confidence that through this in-depth risk assessment we can mitigate potential miscarriages of the protection measurements that can be possibly applied in these certain sub-regions.

To conclude, all these innovative remoting sensing technologies provide the researcher many benefits compared to conventional methods. For instance, they pose great data transferability, completeness, precision and accuracy in the research study. Additionally, due to their capabilities they can produce holistic region measurements, which constitutes very important parameter for the whole geo-engineering society in order to scale up research area without degrading the measurement quality. At last, it is important to highlight UAV ability to eliminate user's risk to get harmed in order to gain access in some inaccessible areas via their remoted technology. This study demonstrates that, they could be considered as a valuable supplemental tool in engineering geology to investigate the quantification of rockfall hazard via a multitemporal change detection analysis and to create an accurate potential failure mechanism model. However, it is significant to mark the importance of fieldwork, site investigation and the geological judgment of the researcher because it is essential to be able to test the validation and the quality of the obtained information.

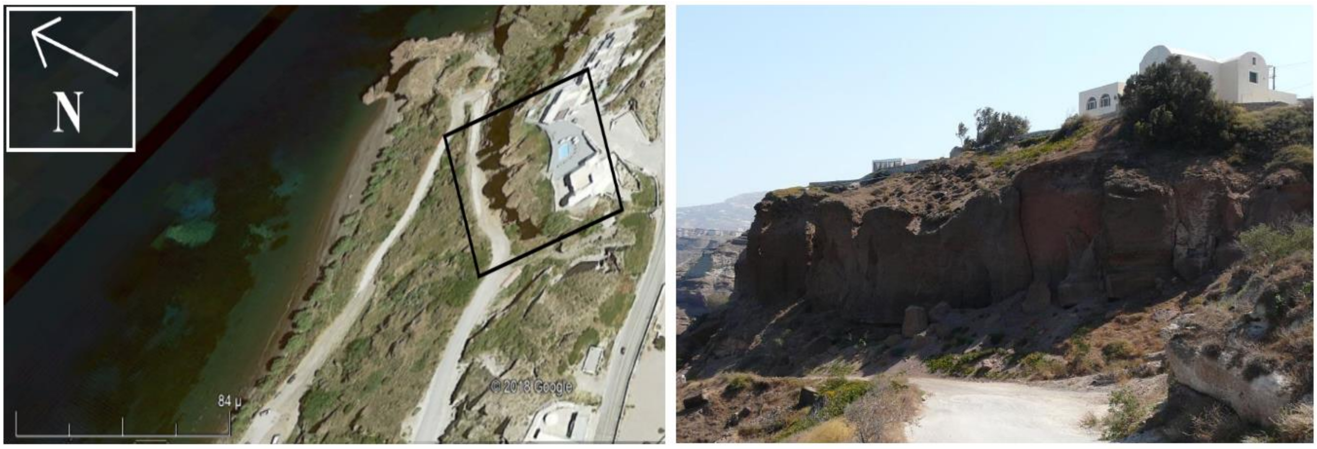

Figure 1. A satellite image of the investigated site "Apothikes" via Google Earth and a close-up image (Marinos et al., 2014) of the prone sub-region that is marked in the first figure.

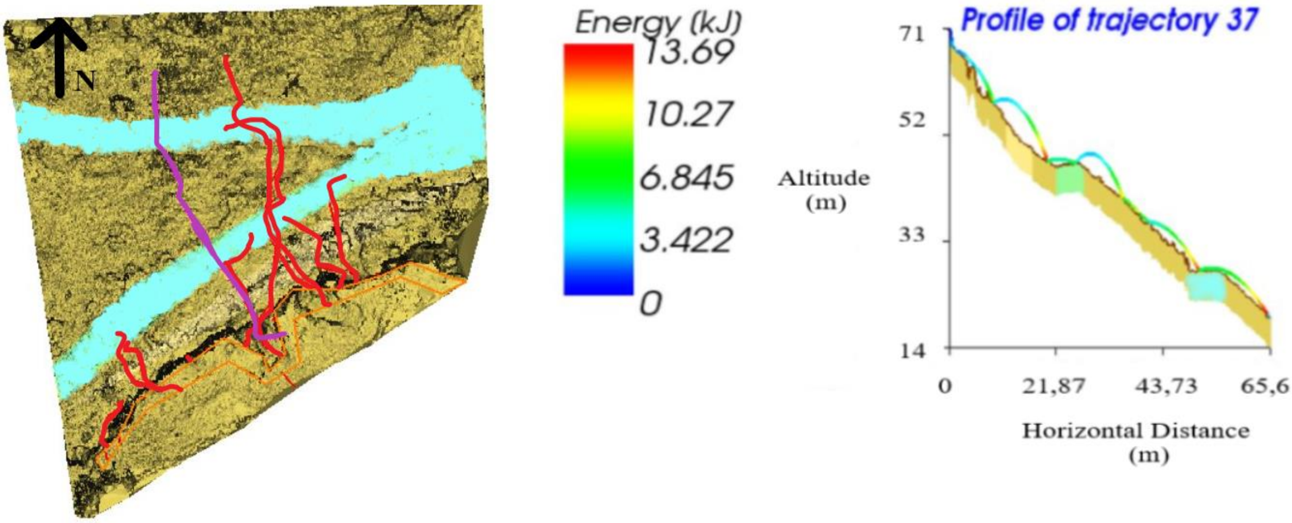

Figure 2. Example of a trajectory analysis (purple one) with energy output that have been applied in the prone sub-region of Figure 1. With light blue color is highlighted the road that leads to the beach.

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